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RESEARCH MEMORANDUM

BLOW-OUT VELOCITIES OF VARIOUS PETROLEUM, SLURRY, AND
HYDRIDE FUELS IN A $1\frac{7}{8}$ -INCH DIAMETER COMBUSTOR

By Preston N. Cook, Jr., Albert M. Lord, and Samuel Kaye

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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LANGLEY AERONAUTICAL LABORATORY
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RESEARCH MEMORANDUMBLOW-OUT VELOCITIES OF VARIOUS PETROLEUM, SLURRY, AND
HYDRIDE FUELS IN A $1\frac{7}{8}$ -INCH DIAMETER COMBUSTOR

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SUMMARY

A $1\frac{7}{8}$ -inch inside-diameter combustor has been developed which can be used to measure and compare the blow-out velocities of single-component fuels, slurries, and fuel mixtures having a wide range of reactivity and physical properties.

The blow-out velocities of isooctane, n-heptane, isopentane, allyl chloride, and propylene oxide varied in the same way as the flame speeds of these fuels determined by the Bunsen flame method. The blow-out velocity of 50-percent 1.5-micron magnesium slurry was much higher than that of the 50-percent 15-micron magnesium slurry. The blow-out velocity of JP-4 was not increased by the addition of 50-percent boron. However, the addition of 3-percent pentaborane in JP-4 substantially increased its blow-out velocity, and 40-percent pentaborane in JP-4 had a blow-out velocity that approached that of 50-percent 1.5-micron magnesium slurry.

INTRODUCTION

The use of metal-hydrocarbon slurries and metal hydrides as fuels in jet-engine propulsion systems has been the subject of analytical and experimental investigation at the NACA Lewis laboratory. Analytical investigations have shown that a higher theoretical air specific impulse is obtainable with these fuels than with hydrocarbons alone when compared at the same equivalence ratio (ref. 1). Experimental investigations reported in references 2 to 6 have shown that metal-hydrocarbon slurries and metal hydrides exhibit high combustion efficiencies, high air specific impulse, and wide combustion limits. Some of the high-energy fuels are costly and are available only in extremely limited quantities. In addition, considerable development work on fuel systems and combustor components is generally required before the fuels can be evaluated. Inasmuch as the design of a high-energy fuel combustor is accomplished by modifying a conventional combustor, it is desirable to possess some quantitative comparison of the combustion performances of

the new fuel and the conventional fuels. For the case of hydrocarbon-type fuels, the laminar flame speeds and the physical properties constitute such combustor-performance indices. The conventional apparatus used in evaluating hydrocarbon fuels is not adaptable to many unconventional fuels because it requires such conditions as (1) a homogeneous gas mixture of fuel and oxidant and (2) nonturbulence. These conditions are a practical limitation for fuels like slurries which contain suspended solids, for fuels such as fuel oils containing high boiling fractions, and for fuels of extremely high reactivity. Therefore, it was necessary to develop a method of comparing their reactivity with fuels of known flame speeds.

In reference 7 it was shown that the flame speed of fuels is related to the blow-out velocity in combustors with bluff bodies, and an experimental investigation (ref. 8) with a ram-jet combustor showed a relation between fuel flame speed and impulse efficiency. In earlier work reported in references 3 to 5, a comparison of the blow-out velocities was used in comparing the reactivities of several slurry fuels. The burner used in reference 5 was limited in range of combustor velocity and in ability to handle highly reactive fuels.

The object of this investigation was to compare the combustion properties of several high-energy fuels with the properties of more conventional hydrocarbon-type fuels in an apparatus whose performance would not be grossly influenced by the physical characteristics of the fuels.

In the investigation reported herein, blow-out velocities were determined for the following: residual fuel oils 4 and 4A; *n*-heptane; isooctane; isopentane; allyl chloride; propylene oxide; MIL-F-5616 grade JP-1; MIL-F-5624A grade JP-4; mixtures of 3-, 10-, 20-, and 40-percent (by weight) pentaborane in JP-4; and slurries of 1.5- and 15-micron magnesium and 1- and 0.7-micron boron in JP-4 fuel.

The experimental work was done at the NACA Lewis laboratory.

APPARATUS AND PROCEDURE

Installation

The combustor and the fuel system are shown in figure 1(a). The flow of air entering the burner was regulated with a throttling valve and measured with a sharp-edged orifice at the high air flows and with a rotameter at the low air flows. The fuel flow was regulated and measured by metering the hydraulic fluid which displaced the fuel above the piston. Because of the corrosiveness, spontaneous inflammability, and toxic properties of pentaborane, the fuel system shown in figure 1(b) incorporating all metal parts except for seals made of Teflon was used

for the pentaborane plus JP-4 mixtures. The combustor details are shown in figure 2. Fuels were atomized with metered air and injected through the porous walls of the mixture preparation zone. The mixing chamber opened directly into a cylindrical chamber which was $1\frac{7}{8}$ -inch inside diameter and 8 inches long. The sudden expansion from the mixing chamber to the combustion chamber acted as a flame holder.

An acetylene-air torch ignited the fuel-air mixture in the combustion chamber through a 1/4-inch hole located in the upstream end of the combustion chamber. The torch was mechanically linked so that the hole could be closed after ignition.

The combustor exhausted to the atmosphere; the exhaust was then induced into a 6-inch-diameter exhaust system containing extensive water sprays for exhaust-product treatment.

Combustor Development

Several combustor designs were used in the attempt to evaluate the fuels with a variety of physical properties. These designs incorporated flame holders of the conventional V-gutter, can, and cone designs. All were unsatisfactory because of the tendency of the particles in slurry fuels to collect on the upstream surfaces of the flame holder and then break away at various intervals so that the instantaneous fuel-air ratio, pressure drop, and hence burner velocity at which blow-out occurred varied unpredictably. The design which appeared to be the least affected by the above conditions is shown in figure 2. This combustor incorporated the following design features:

(a) A high-velocity mixture-preparation zone. - The mixture preparation zone was designed to eliminate air-flow recirculation and provide velocities sufficient to suspend and carry through liquid and solid fuel particles.

(b) Sudden expansion flame-holding system. - The area change used to produce the turbulence essential for flame seating and flame propagation was arranged to reduce the impingement of solid and liquids on surfaces.

(c) Porous walls in the mixing chamber. - Despite the high velocities in the mixing chamber, in the case of some fuels it was necessary to film the surface of the mixture-preparation zone with air. This was achieved by passing the combustion air through the 20X200 mesh wire cloth. The wire cloth was coated once on each side by a silver-alloy brazing process in order to obtain the desired permeability and stiffness as de-

(d) Air-atomizing fuel nozzle. - In the course of the combustor development, it was found that the stability limits of the more viscous fuels were affected by the fineness of the fuel spray and hence were affected by the fuel pressure of conventional fuel nozzles. The use of an air-atomizing fuel nozzle apparently gave a more consistent spray for the fuels investigated. The blow-out velocities of several fuels were checked with various amounts of atomizing air and various fuel pressures in the fuel atomizer. Plateaus of operation were found in which the blow-out velocities were essentially independent of air- and fuel-pressure variations over moderate ranges. These plateaus of operation coincided with regions of consistent fuel-spray formation. The operating condition of the fuel atomizer for this region of operation was: atomizing-air annulus, 0.01-inch width, 1/4-inch mean diameter; atomizing-air pressure, 40 pounds per square inch gage; fuel-nozzle opening, 0.020- to 0.080-inch diameter as selected to accommodate fuels of different flow rates and viscosities.

Test Procedure

For the determination of the blow-out limits, the atomizing-air flow was held constant, a steady fuel flow was maintained, and the secondary-air flow was set low enough for ignition of the fuel-air mixture and was gradually increased until flame failure occurred.

The velocity at blow-out was computed from the air flow at a reference area corresponding to the combustion-chamber inlet (1 $\frac{7}{8}$ -in. diameter) with atmospheric pressure and temperature assumed.

The air temperature varied from 60° to 90° F, and the humidity was not controlled although a water separator removed water droplets in the inlet-air line. Reference 9 reported that humidity can make a change of as much as 6 percent in the burning velocity of propane.

Fuels and Fuel Properties

The following fuels were used in this investigation:

Fuel	Powder particle size, microns	Powder purity, percent	Viscosity at 30° C, centipoises	Remarks
MIL-F-5624A grade JP-4	---	--	---	Table I
MIL-F-5616 grade JP-1	---	--	---	Table I
n-Heptane	---	--	---	A.S.T.M. grade
Isopentane	---	--	---	Technical grade
Isooctane	---	--	---	A.S.T.M. grade
Allyl chloride	---	--	---	Commercial grade
Propylene oxide	---	--	---	Commercial grade
Fuel oil 4A	---	--	5.0	Table I
Fuel oil 4	---	--	18.0	Table I
50-Percent magnesium, 50-percent JP-4	1.5	83	2975	
50-Percent magnesium, 50-percent JP-4	15	93	1000	Gel, 0.6 percent
50-Percent boron, 50-percent JP-4	1.0	90	1350	G-672, 1.6 percent
50-Percent boron, 50-percent JP-4	.7	97	5000	G-672, 1.3 percent Gel, 0.5 percent
3-Percent pentaborane, 97-percent JP-4	---	--	----	
10-Percent pentaborane, 90-percent JP-4	---	--	----	
20-Percent pentaborane, 80-percent JP-4	---	--	----	
40-Percent pentaborane, 60-percent JP-4	---	--	----	

The particle size designations used herein to describe the powders were determined with a Fisher Sub-Sieve Sizer. This instrument employs the air permeability method for measuring average particle size of a powder.

The gelling agent was an aluminum octoate soap.

A surface-active agent designated G-672 was used to decrease the viscosity of some of the slurries. This is a commercial preparation containing glycerol sorbitan laurate as the active ingredient.

The viscosities were determined with a Brookfield Synchro-electric viscometer. The measurements were all made at 30° C at a spindle speed of 12 rpm, 30 seconds after the spindle was started. The spindle speed and timing for taking the viscosities were held constant because the slurries are non-Newtonian fluids.

RESULTS AND DISCUSSION

A comparison of the blow-out velocities of the fuels is shown in figure 3. When operating near the lean limits (minimum equivalence ratio for supporting combustion), the combustor became erratic because the air flow across the porous wall of the mixing chamber was not sufficient to prevent liquids and solids from depositing on the wall.

Figure 3(a) shows that there is no measurable difference between the blow-out velocities of JP-1 and JP-4 fuels. This curve will be used in subsequent figures for comparison and will be called the "JP reference curve."

Figure 3(b) gives the blow-out velocities of n-heptane, isooctane, isopentane, allyl chloride, and propylene oxide. The blow-out velocities of these single-component fuels vary in the same way as the flame speeds of these fuels determined by the Bunsen flame method. Maximum blow-out velocities and the maximum burning velocities, as reported in reference 8, of fuels of widely varying boiling points are shown in figure 4.* A reasonable correlation between the maximum burning velocity of the Bunsen flame method and the blow-out velocity is evident. For the range investigated, the boiling point of these fuels has little influence on the blow-out velocity compared with the effect of burning velocity.

The blow-out velocities of residual fuel oils 4 and 4A as shown in figure 3(c), however, are substantially lower than those of the JP fuels; fuel volatility may well account for this difference. The blow-out

*The maximum burning velocity of isopentane was estimated from unpublished NACA data.

velocities of these fuels were measured with a similar apparatus and were reported in reference 5. The burner used in reference 5 gave the same blow-out velocity curve for both fuel oils.

The blow-out velocities of the magnesium-slurry fuels are shown in figure 3(d). The 50-percent 1.5-micron slurry gave the highest blow-out velocities of any of the fuels. It was impossible to obtain a blow-out velocity above an equivalence ratio of approximately 0.7 because the maximum air flow of the apparatus (260 ft/sec) did not cause blow-out. The choice of the location of the curve through the scattered data points was influenced by the data on $4\frac{1}{2}$ - and 2-micron 50-percent magnesium slurries in references 4 and 5, respectively. The 50-percent 15-micron magnesium slurry has a much lower blow-out velocity than the smaller particle slurry. This lower velocity (as was noted in ref. 5) reflects the higher reactivity of the smaller magnesium particles. The addition of 50-percent 15-micron magnesium to JP-4 increases the blow-out velocity so that it approaches that of propylene oxide.

The blow-out velocities for the boron slurries are shown in figure 3(e). It is seen that a single curve could be drawn through the data points of both the low- and high-purity boron slurries and that this curve would coincide with the JP reference curve. Neither of the boron powders increased the reactivity of the JP-4 carrier fluid.

The effect of pentaborane additive on the blow-out velocity of JP-4 is shown in figure 3(f). As little as 3-percent addition of pentaborane to JP-4 made a substantial increase in the blow-out velocity. A 20-percent pentaborane blend exhibited about the same blow-out velocities as propylene oxide at comparable equivalence ratios. At 40-percent pentaborane concentration, it was possible to burn at lean mixtures, but the explosions that accompanied reignition after blow-out were so violent that the compression waves drove the boric oxide particles upstream into the mixing-chamber screen and quickly clogged it. At 40-percent pentaborane concentration, the blow-out velocity approached that of 1.5-micron 50-percent magnesium slurry (fig. 3(d)) and is considerably higher than the JP reference curve.

It is noted that the blow-out velocities of pentaborane - JP-4 mixtures increase almost linearly as the equivalence ratio increases above the stoichiometric ratio. In contrast, the single-component fuels approach an asymptotic maximum as the equivalence ratio exceeds the stoichiometric ratio. A similar effect was described in reference 3 where magnesium-hydrocarbon slurry combustion products were sampled and analyzed to show that at mixture ratios above stoichiometric the more reactive constituent (magnesium) burned preferentially and the "effective ratio" of metal to hydrocarbon utilized in the combustion increased with equivalence ratio. This concept of the combustion mechanism of fuel mixtures that consist of components of different reactivity

suggests that the blow-out velocity increase at equivalence ratios in excess of stoichiometric is due to the fact that the more reactive component becomes an increasingly larger fraction of the burned portion of the fuel.

SUMMARY OF RESULTS

A $1\frac{7}{8}$ -inch inside diameter combustor has been developed which can be used to measure and compare the blow-out velocities of single-component fuels, slurries, and fuel mixtures having a wide range of reactivity and physical properties. The following results have been obtained from this combustor:

1. There was no measurable difference between the blow-out velocities of JP-1 and JP-4 fuels.
2. The blow-out velocities of isooctane, n-heptane, isopentane, allyl chloride, and propylene oxide varied in the same way as the flame speeds of these fuels determined by the Bunsen flame method.
3. The blow-out velocities of residual fuel oils 4 and 4A were lower than the velocities of the JP fuels.
4. A much higher blow-out velocity was obtained with 50-percent 1.5-micron magnesium slurry than with 50-percent 15-micron magnesium slurry, and the latter had a blow-out velocity that approached that of propylene oxide.
5. A 50-percent addition of boron in JP-4 did not increase the blow-out velocity over that of JP-4 alone.
6. A 3-percent addition of pentaborane in JP-4 substantially increased the blow-out velocity. At 40-percent pentaborane concentration in JP-4, the blow-out velocity approached that of 50-percent 1.5-micron magnesium slurry, both velocities being considerably higher than that of the reference JP fuels.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, January 25, 1954

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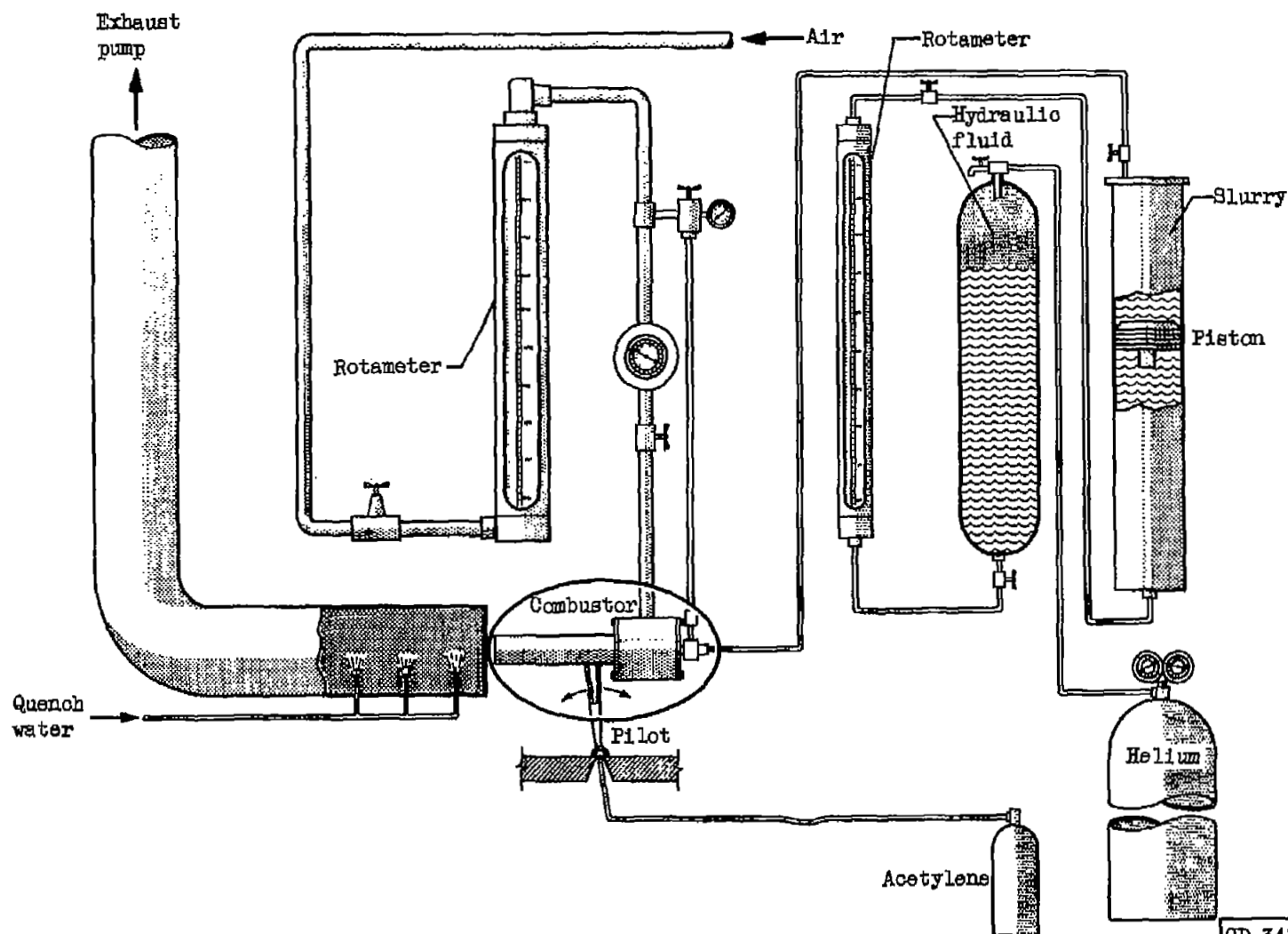
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TABLE I. - CARRIER FLUID PROPERTIES

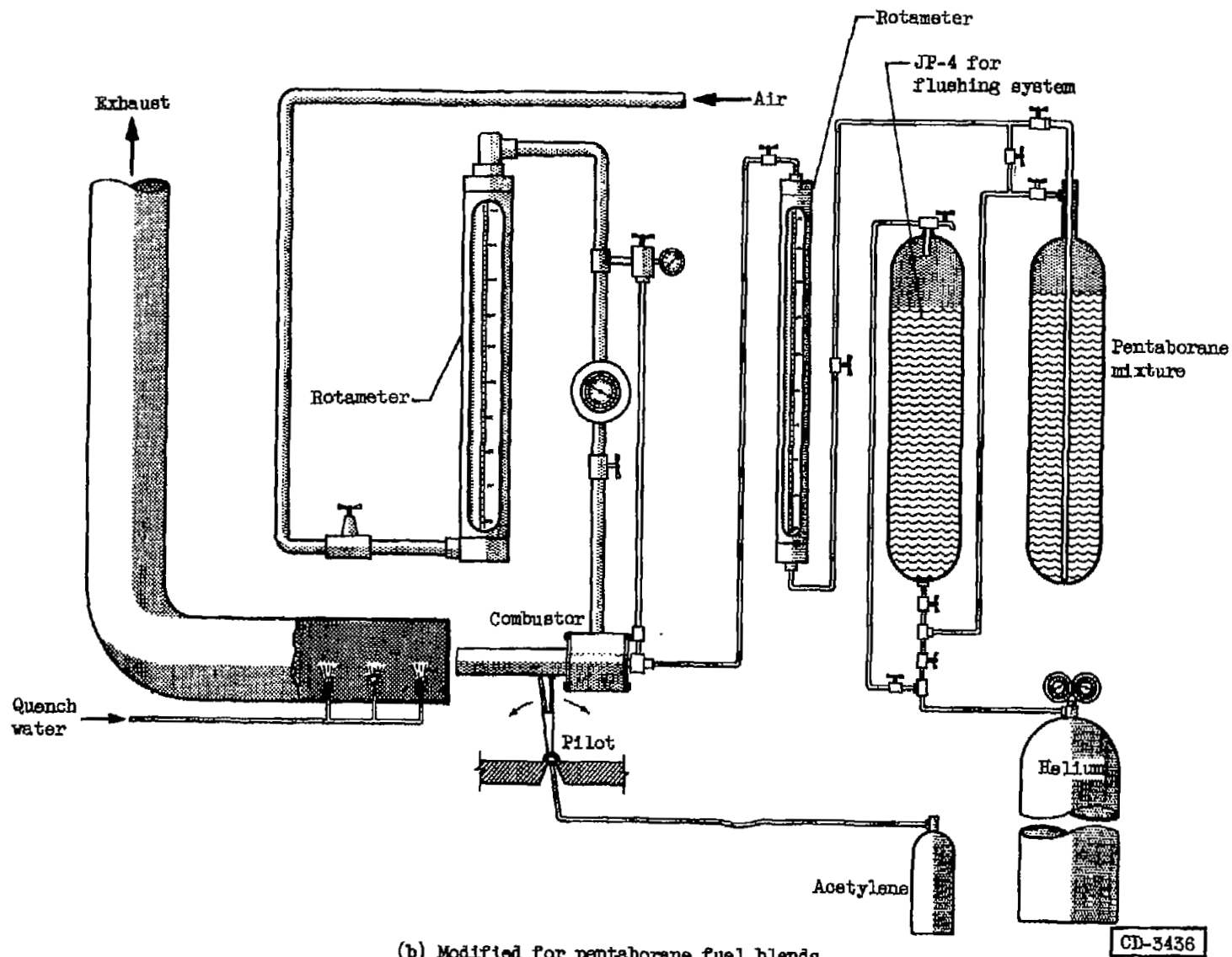
Properties	MIL-F-5624A grade JP-4 fuel	MIL-F-5616 grade JP-1 fuel	Fuel oil	
			Number 4A	Number 4
Initial boiling point, °F	140	313	395	444
Percent evaporated				
5	199	331	430	484
10	222	339	438	499
20	248	346	450	517
30	268	351	461	532
40	286	358	474	551
50	300	368	487	572
60	325	377	501	604
70	348	382	518	646
80	382	396	540	676
90	427	413	571	(a)
95	459	423	603	
Final boiling point, °F	488	443	647	
Residue, percent	1	1	1.8	
Reid vapor pressure, lb/sq in.	2.5	0	Negligible	Negligible
Specific gravity at 60° A.P.I.	52.8	-----	31.3	27.7
Specific gravity at 60°/60° F	0.768	0.797	0.869	0.889
Hydrogen-carbon ratio	.167	.167	.139	.145
Heat of combustion, Btu/lb	18,675	18,600	18,260	18,130

^aDistillation incomplete because of cracking.



(a) Original installation.

Figure 1. - Test installation used to determine blow-out velocities of fuels.



(b) Modified for pentaborane fuel blends.

Figure 1. - Concluded. Test installation used to determine blow-out velocities of fuels.

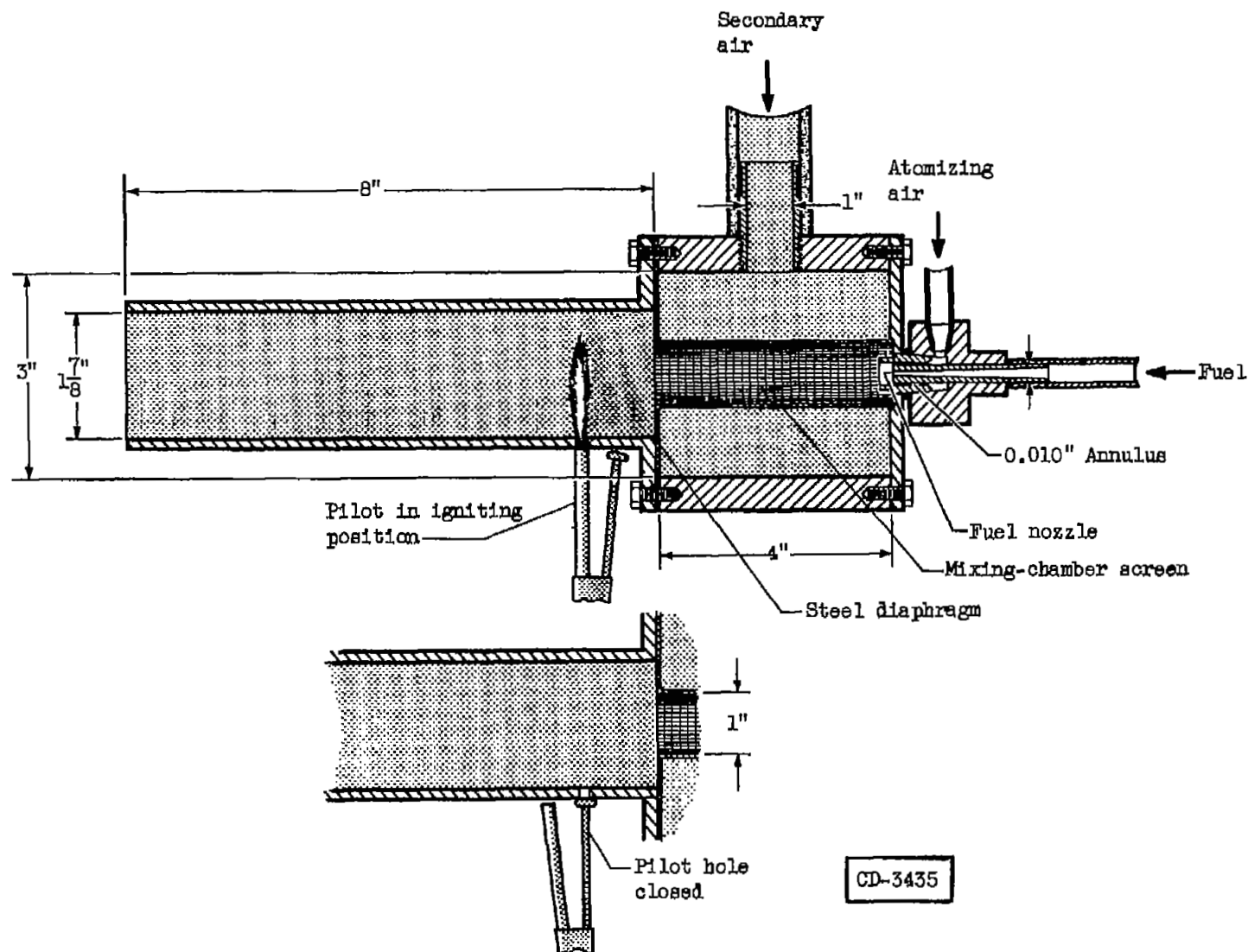
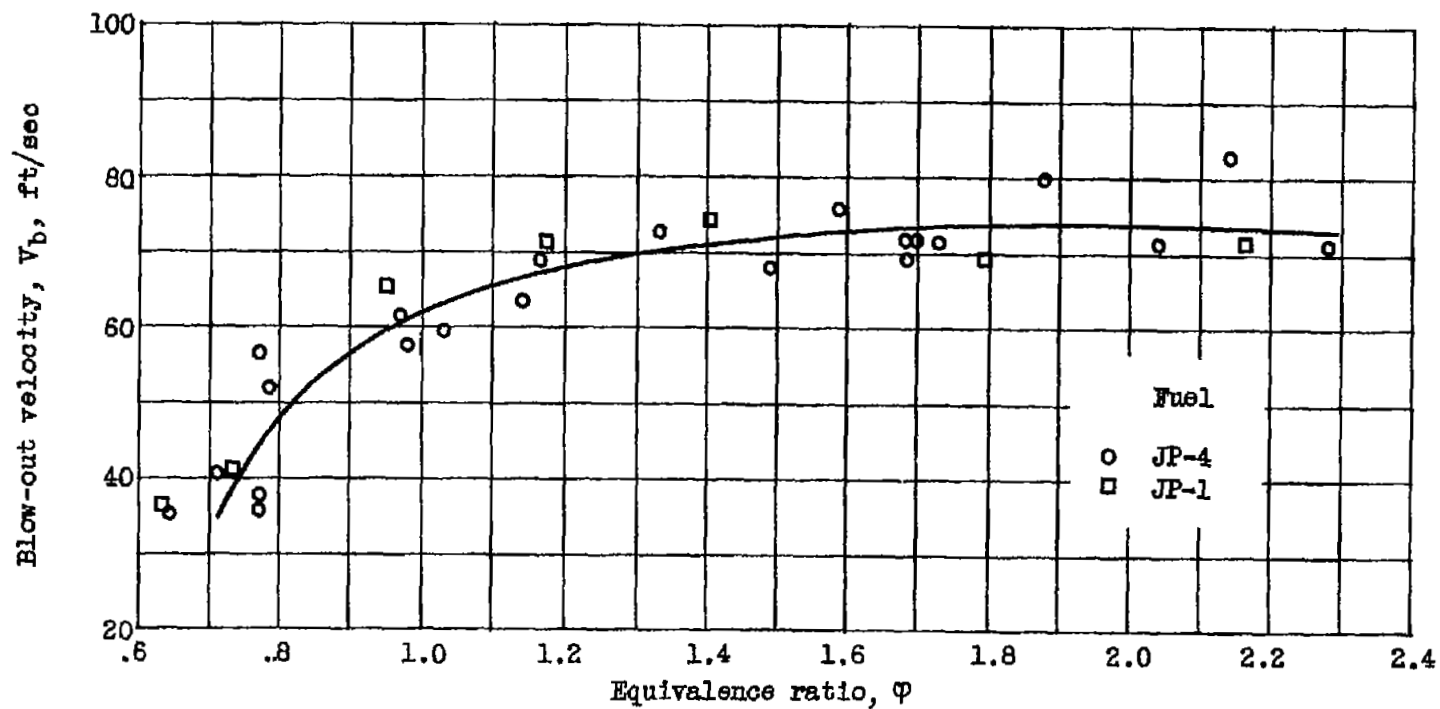
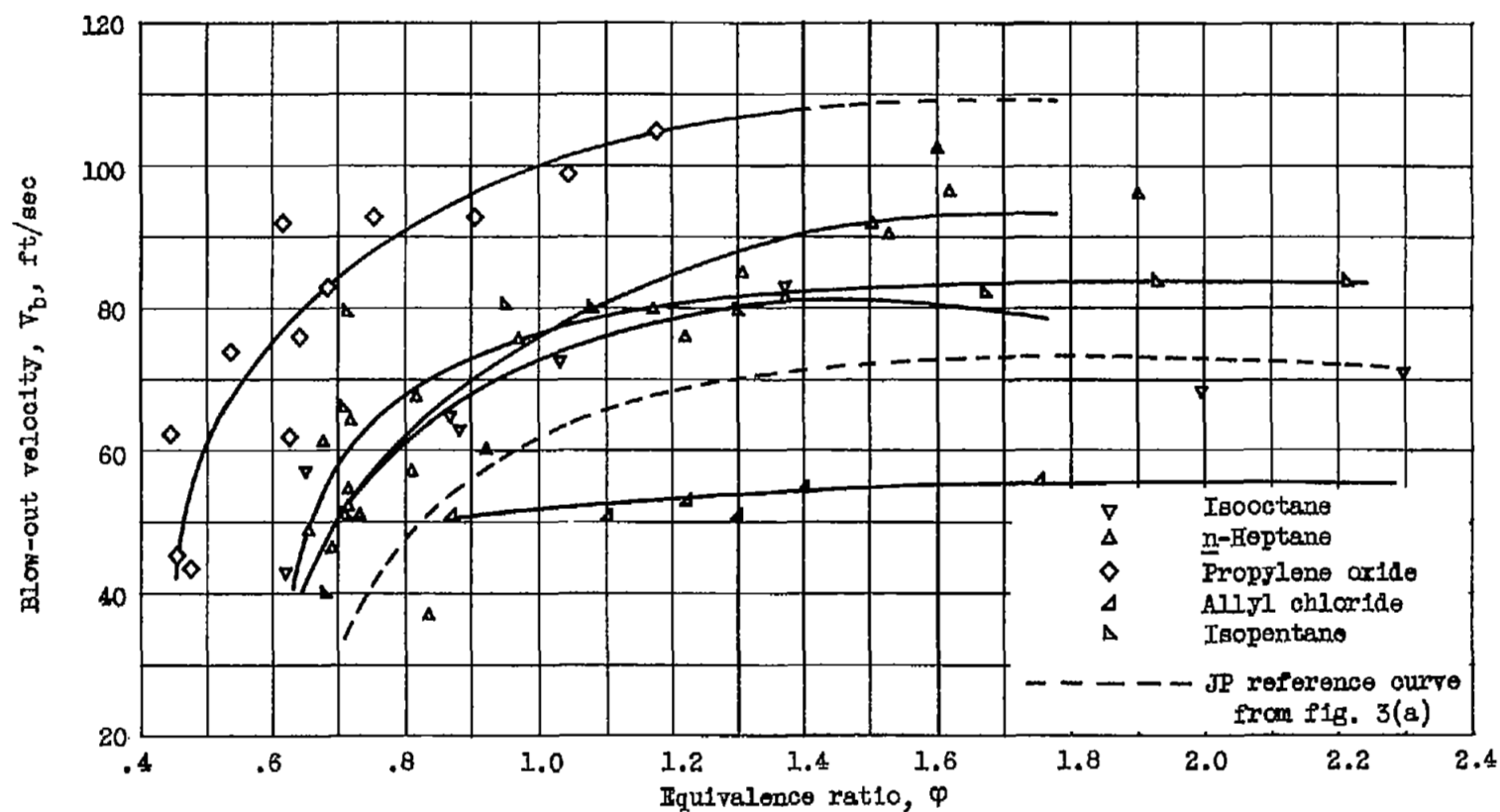


Figure 2. - Combustor, pilot, and mixing chamber.



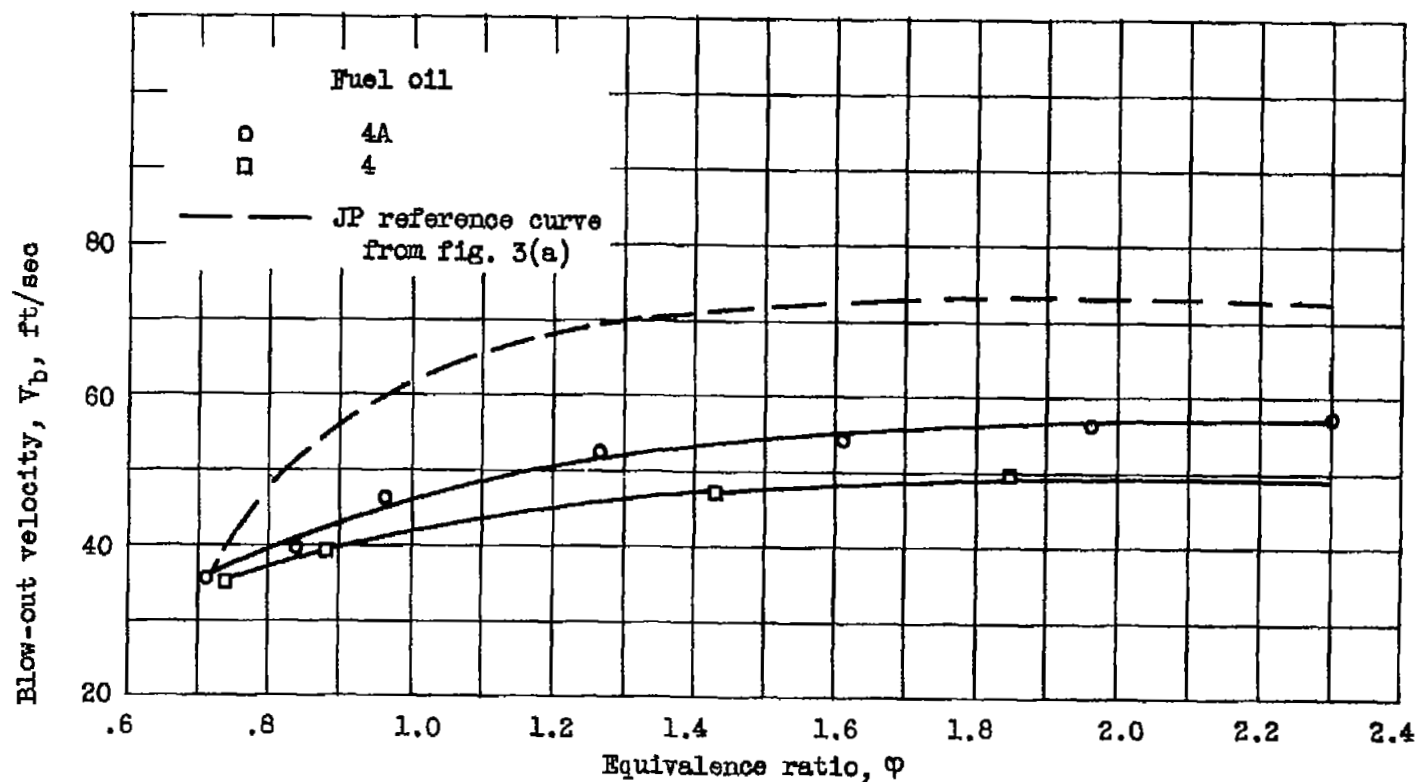
(a) JP-1 and JP-4 fuels.

Figure 3. - Blow-out velocities of various fuels.



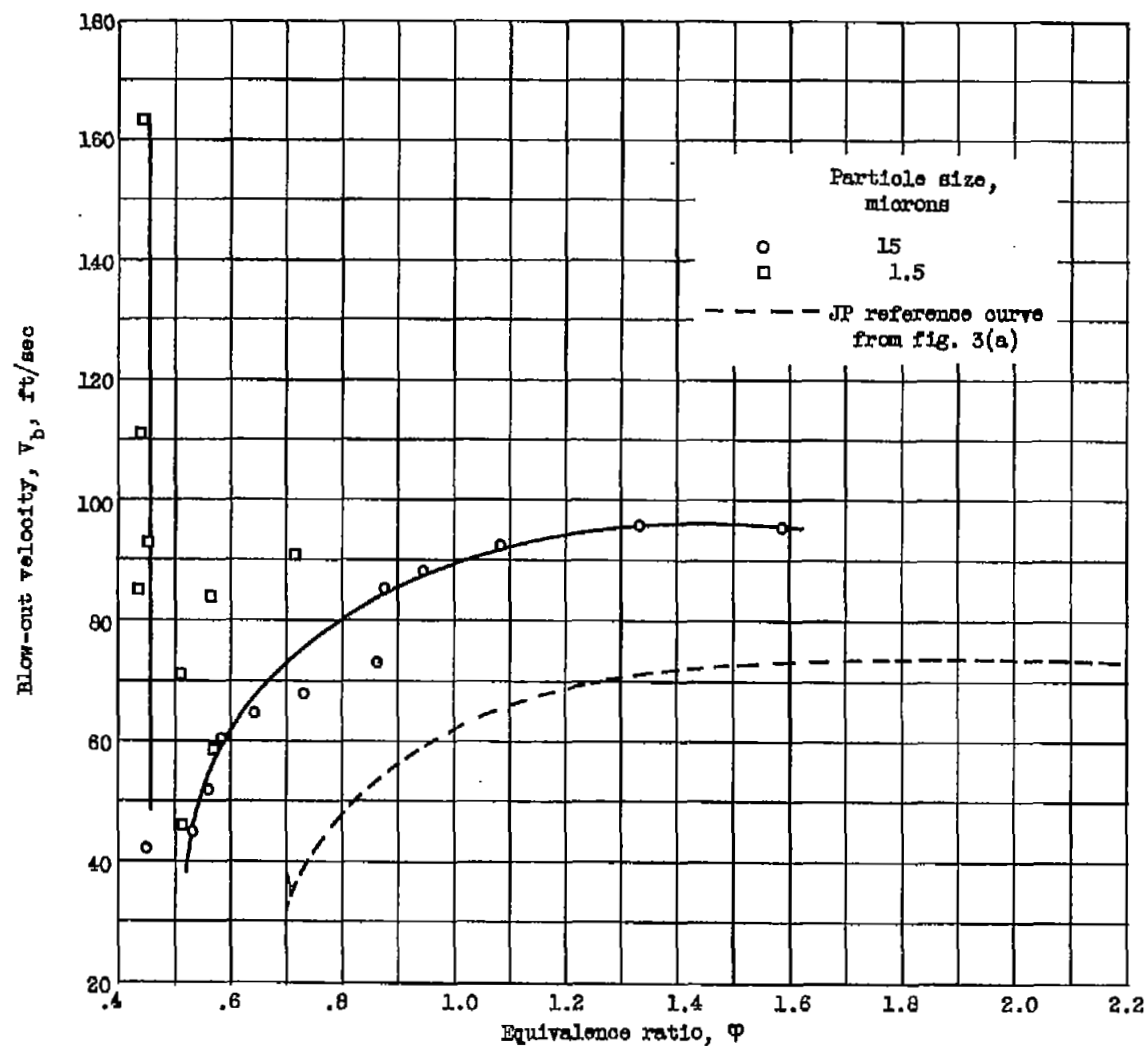
(b) Several component fuels.

Figure 3. - Continued. Blow-out velocities of various fuels.



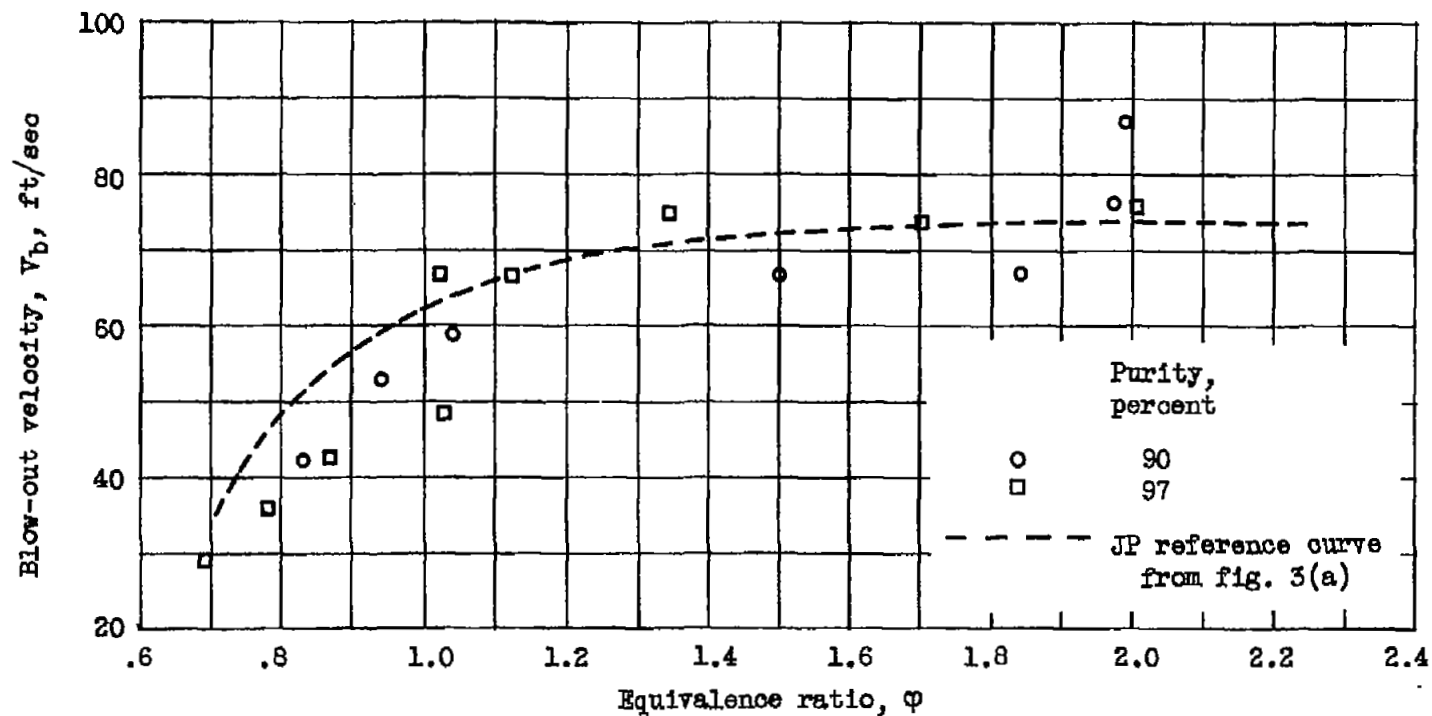
(c) Two residual fuel oils.

Figure 3. - Continued. Blow-out velocities of various fuels.



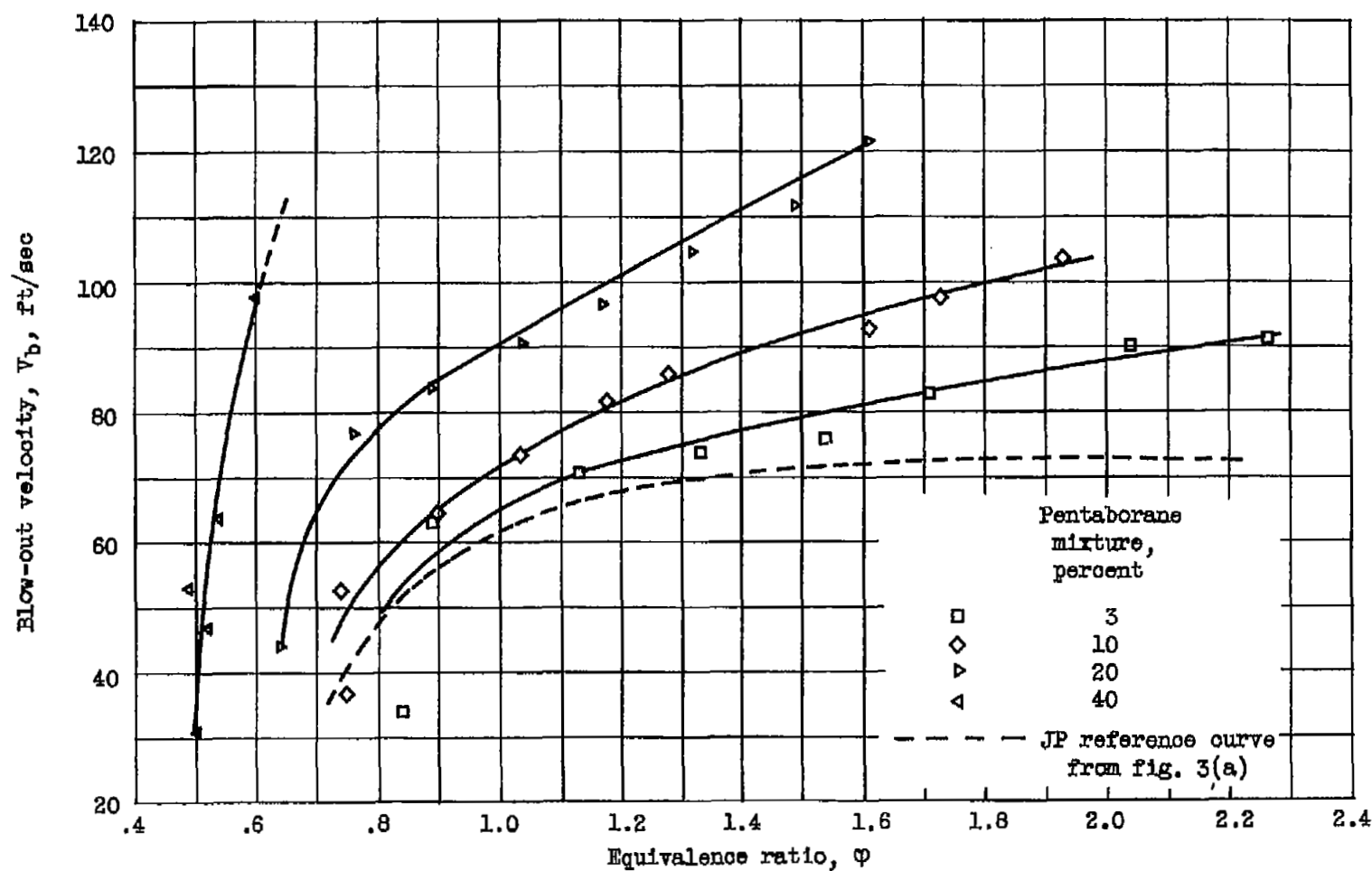
(d) Two 50-percent magnesium slurries.

Figure 3. - Continued. Blow-out velocities of various fuels.



(e) Two 50-percent boron slurries.

Figure 3. - Continued. Blow-out velocities of various fuels.



(f) Four mixtures of pentaborane in JP-4 fuel.

Figure 3. - Concluded. Blow-out velocities of various fuels.

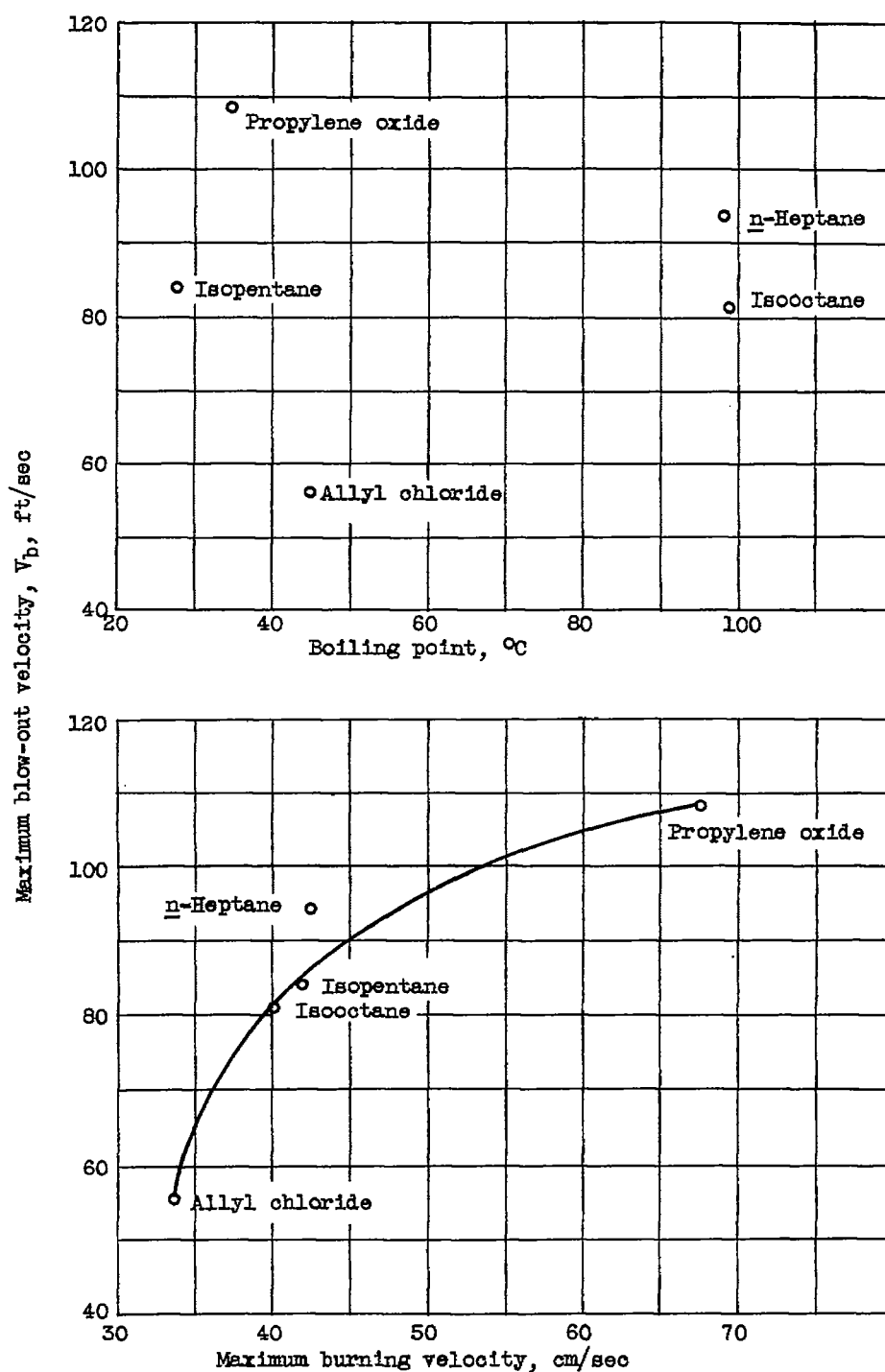


Figure 4. - Comparison of maximum burning velocities and boiling points with maximum blow-out velocities.

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